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13. ABSTRACT (Maximum 200 words)

GaAs epilayers grown at low substrate temperatures by molecular beam epitaxy contain arsenic antisites and gallium vacancies. With anneal these point defects form arsenic precipitates. We have investigated GaAs epilayers with a wide range of excess arsenic concentrations and anneal conditions to study the role of the point defects and arsenic precipitates in carrier trapping and recombination. we have determined the electron and hole capture cross sections for the arsenic antisite in LTG-GaAs of $\sigma_n = 7x10^{-15}$ cm^2 and $\sigma_p = 6x10^{-17}$ cm^2 respectively. We have also shown the concentration of arsenic antisites in annealed LTG-GaAs is not sufficient to account for the short carrier lifetimes. In addition, the recombination of electron-hole pairs in annealed LTG-GaAs is single exponential, which would not be the case for a trap with a large difference in electron and hole capture cross-sections as the arsenic antisite. Since the arsenic antisites and gallium vacancies are disappearing with anneal, and it is unlikely another defect of significant concentration is being formed, we conclude that the arsenic precipitates are the source of the short carrier lifetimes. Also, since the differential transmission transients become single exponential with anneal and formation of the arsenic precipitates, the arsenic precipitates must have comparable electron and hole capture cross-sections.

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Final Technical Report on

(AASERT-92) Arsenic Cluster Engineering for High Speed Photoconductors

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April 1997

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Students Supported

Three graduate students were supported during the course of this ASSERT, Eric Harmon, Steve Carin, and Tony Lochtefeld. Eric received his Ph.D. and formed a start-up company, MellWood Laboratories, Incorporated. He recently announced his first product, a high-speed photodetector based on LTG-GaAs. This represents a transfer of the technology Eric helped develop as a graduate student to the marketplace. An advertisement for this product that appeared on the back cover of the January 20, 1997 issue of Applied Physics Letters is attached at the end of this report. Tony Lochtefeld received his MSEE and then transferred to MIT to pursue his Ph.D. Steve Carin received his MSEE and took a position with Lincoln Laboratories.

Carrier Trapping and Recombination in LTG-GaAs

The students supported by this ASSERT conducted a thorough investigation of the role of point defects and arsenic precipitates in carrier trapping and recombination by investigated LTG-GaAs epilayers with a wide range of excess arsenic concentrations and anneal conditions. The samples investigated were grown in a GEN II MBE system on semi-insulating GaAs substrates at a growth rate of 1 μm/h and an As_2-to-Ga beam equivalent pressure of 20. The substrate temperature during MBE was used to control the amount of excess arsenic in the LTG-GaAs region. The epilayer structure is shown in Fig. 1. The LTG-GaAs region was 1 μm thick and clad with 50 nm $Al_{0.3}Ga_{0.7}As$ layers. Below this double heterostructure was a 20 nm AlAs layer and a 0.5 μm $Al_{0.5}Ga_{0.5}As$ layer so that the double heterostructure could be removed using either epilayer lift-off or substrate etching to facilitate transmission measurements. Two methods were used for removing the substrates to insure that the substrate removal technique did not influence the measured carrier transients. These epilayers were attached to glass slides for handling. Before substrate removal, some samples were annealed to cause the excess arsenic to precipitate. The isochronal anneals were of 30 s duration and ranged from 600 °C to 800 °C. These anneals cause the excess arsenic to precipitate and coarsen. The 600°C 30 s anneal is sufficient to cause most of the excess arsenic to precipitate. The higher the temperature of the anneal, the larger and less dense are the precipitates, but the total amount of arsenic in the precipitates is approximately the same for all anneal conditions. TEM on the annealed epilayers was used to determine the amount of excess arsenic in the epilayers.

A pump/probe differential transmission measurement technique, as illustrated in Fig. 2, was used to measure the carrier trapping and recombination in both the as-grown and the annealed epilayers. An increase in transmission occurs with the photogeneration caused by the pump pulse because of band filling. A transient in the transmission occurs as these photogenerated carriers recombine or become trapped. Because of the large difference in the density of states in the conduction and valence bands, this technique is sensitive to the electron population in the conduction band. A probe pulse was used to measure the transient in transmission. The path length of the probe pulse was varied to enable measurement of the transients. The optical pulses were of 150 fs duration and tuned to a photon energy of just above the bandgap of GaAs to minimize carrier cooling effects. The typical pump pulse beam energy was 660 pJ focused to a spot size of 50 μm. The probe pulse beam energy was 16 pJ and was focused to a spot size of 30 μm.

The measured differential transients are shown in Fig. 3 for three epilayers. The excess arsenic concentrations in these epilayers are 0.52%, 0.25%, and 0.02%. For the two epilayers with the higher excess arsenic concentrations, a fast initial transient is observed followed by a very slow transient. This initial fast transient is on the order of a couple of hundred femtoseconds whereas the slow transient back to equilibrium is on the order of nanoseconds. Such a long second transient suggests a trapping of the photogenerated holes on separate defects. It is likely that the electrons are being trapped on the arsenic antisites and the holes on the gallium vacancies in these epilayers.

For the sample with the smallest amount of excess arsenic, 0.02%, the concentration of the point defects is low enough that recombination is occurring for most of the photogenerated carriers. The effect of pump pulse energy on the differential transmission transient is shown in Fig. 4. For the lowest pump pulse energy, a clear two-component decay is seen—an initial fast capture of the photogenerated electrons followed by a slower capture of the photogenerated holes. As the energy of the pump pulse is increased, a saturation of the trap states occurs. This saturation results from more electron-hole pairs being created than recombination sites. The traps fill with electrons, and further removal of electrons from the conduction band can occur only after capture of a hole. The 0.02% excess arsenic sample has 1.5×10^{19} cm^{-3} excess arsenic atoms, presumably in the form of arsenic antisites. The saturation levels in the transients in Fig. 4 suggests about $2\text{–}3 \times 10^{17}$ cm^{-3} of these arsenic antisites are ionized in equilibrium, presumably caused by an equivalent concentration of gallium vacancies. From the concentration of ionized and neutral arsenic antisites, and from the transients in Fig. 4, one can estimate the electron and hole capture cross sections for the arsenic antisite defect in LTG-GaAs. The estimated electron capture cross-section is 7×10^{-15} cm^2, and the estimated hole capture cross-section is 6×10^{-17} cm^2. This electron capture cross section is over 50 times larger than the capture cross-section for the arsenic antisite defect know as EL2, which is 1.2×10^{-16} cm^2. Look, et al. (J. of Appl. Phys. 76, 1029, 1994) have pointed out that the arsenic antisite defect in LTG-GaAs is not EL2. Look et al. measured the electron capture cross-section for the arsenic antisite defect in LTG-GaAs using deep level transient spectroscopy and obtained a value of 1.5×10^{-15} cm^{-2}, also more than an order of magnitude larger than the electron capture cross-section of EL2.

Seen in Fig. 3, after anneal the differential transmission transients appear to become single exponential. In fact if the natural logarithm of these differential transients are plotted, as in Fig. 5, they are well fit by a single exponential. The corresponding transient time constants are shown in Fig. 5 and also in Table II. As the anneal temperature is increased from 600 °C, there is an increase in the transient time constant, and for a given anneal condition, lower excess arsenic concentrations in the epilayer yield longer time constants. It is interesting to compare the transient for the as-grown sample with 0.02% excess arsenic to the transients for the annealed epilayers of all excess arsenic concentrations. The lifetime varies from 51 ps for the as-grown 0.02% excess arsenic epilayer to 21 ps after a 600 °C 30 sec anneal. With such an anneal, point defects are being removed from the epilayer. For the lifetime to decrease, the anneal must be creating a new recombination center. The point defect concentration in the as-grown 0.02% excess arsenic sample is higher than the point defect concentrations in the 0.52% or 0.25% excess arsenic samples after the 600 °C or higher temperature anneals. However, the time constant of the 600 °C 30 sec annealed 0.52% excess arsenic sample at 1.5 ps is over an order of magnitude shorter than the 51 ps transient time constant of the as-grown 0.02% excess arsenic sample. Assuming these point defects in the epilayers are similar and only concentrations are changing with substrate temperature during MBE, suggests that the short lifetimes are not due to the point defects in the as-grown materials but caused by the formation with anneal of a new recombination site. Arsenic precipitates are forming with anneal, strongly suggesting they are the source of this increased rate of recombination in annealed LTG-materials.

The technology developed during the course of this ASSERT was transferred to MellWood Laboratories, Incorporated. Shown in Fig. 6 is an advertisement that appeared on the back cover of the January 20, 1997 issue of Applied Physics Letters for MellWood Laboratories' high-speed photodetector based on LTG-GaAs.

Publications Acknowledging Support from this Grant

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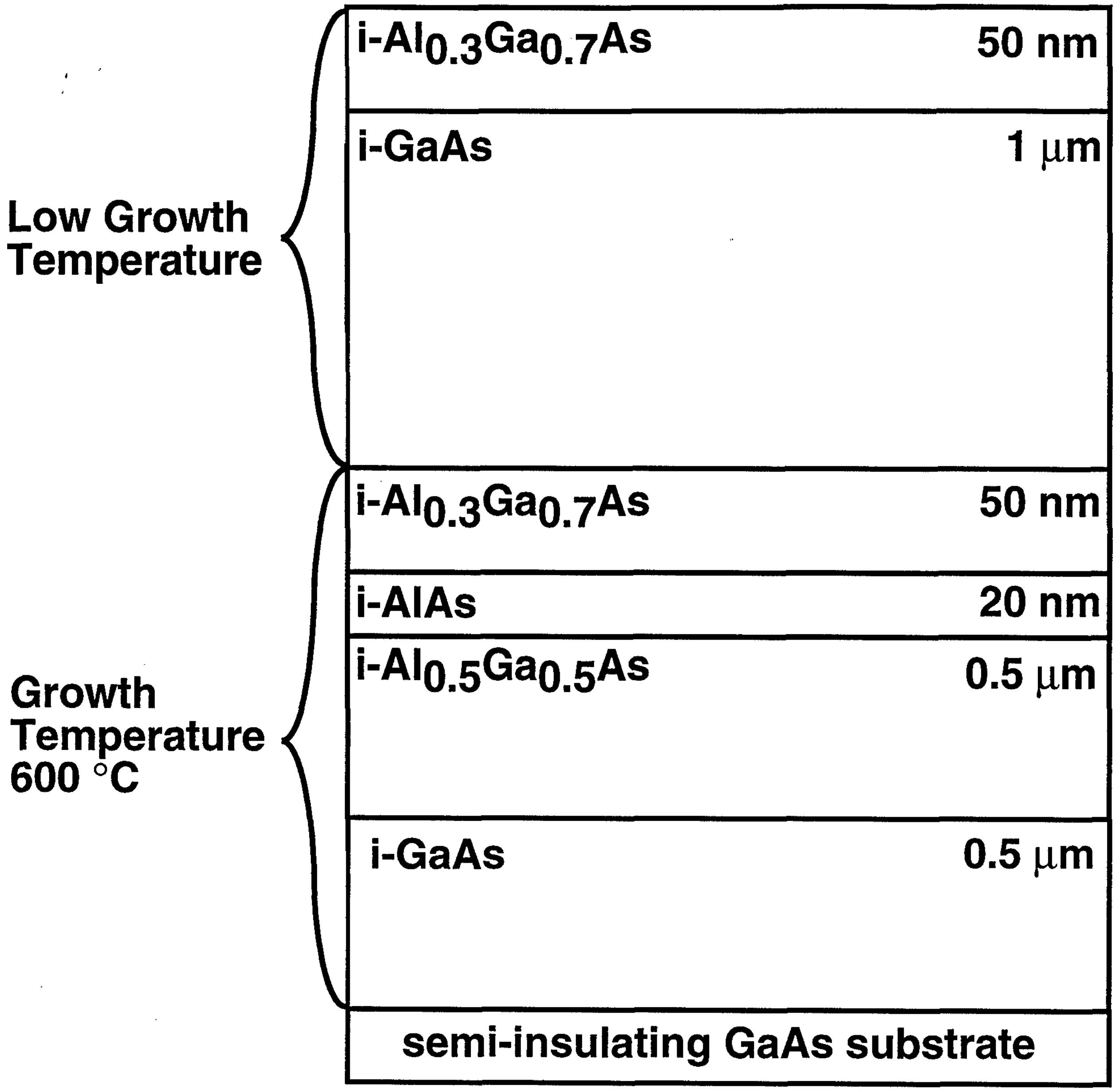
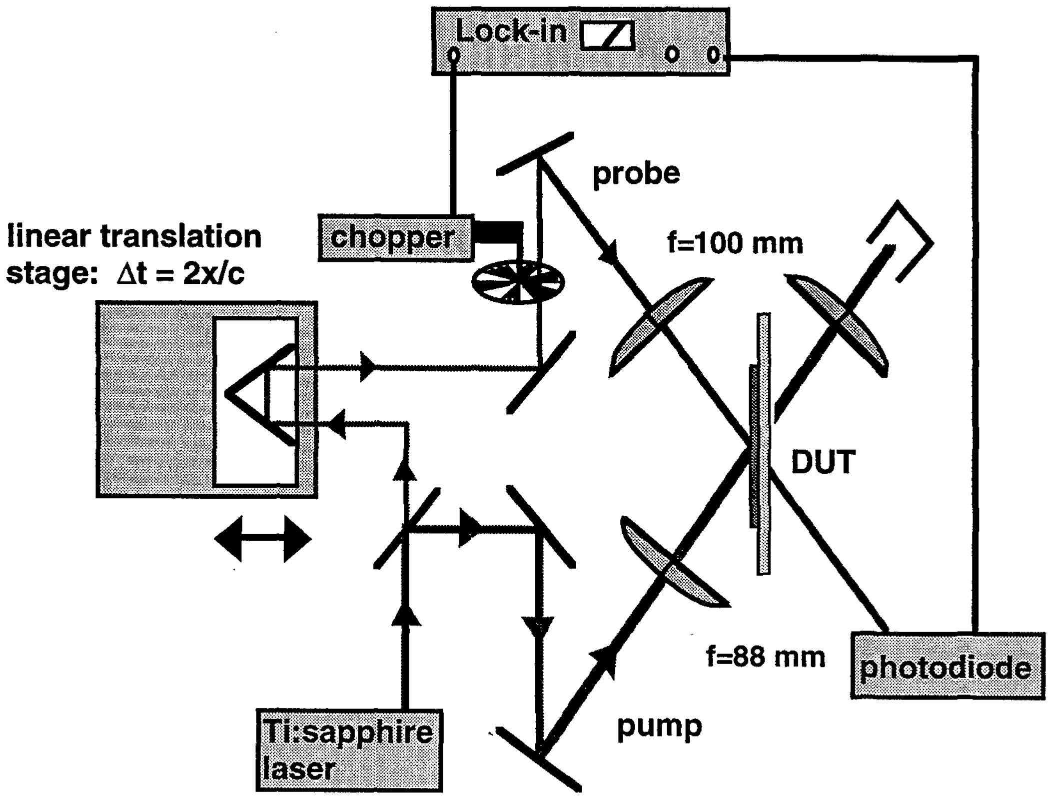


Fig. 1 Film Structure for Lifetime Measurements

Pump/Probe Experimental Setup



pump: 50 µm spot size, 660 pJ
probe: 30 µm spot size, 16 pJ

Fig. 2 Pump/Probe Measurement Technique

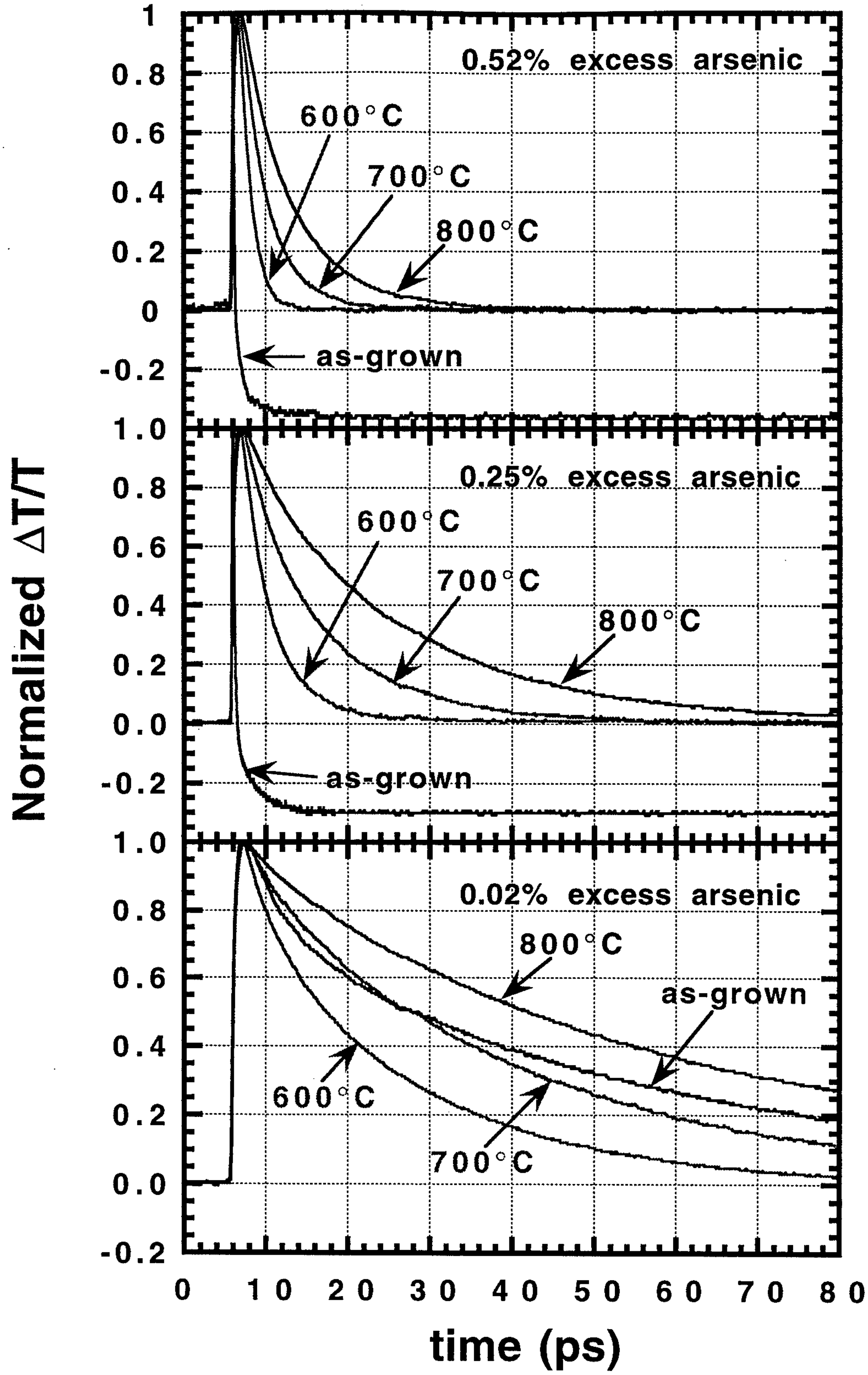


Fig 3. Normalized differential transmission from a pump/probe measurement of three GaAs epilayers containing 0.52%, 0.25%, and 0.02% excess arsenic. Transients are shown for as-grown material and material that has been annealed for 30 s at 600 °C, 700 °C, and 800 °C. The rounded peaks in the longer time scans for the annealed samples are an artifact of the lock-in averaging technique.

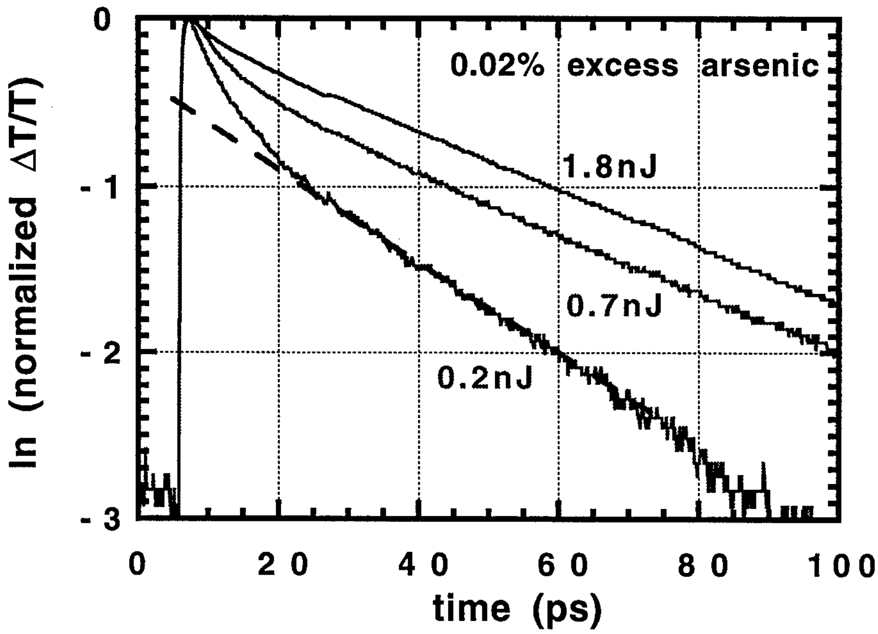


Fig 4. Normalized differential transmision with varying pump pulse energy for the as-grown GaAs epilayer containing 0.02% excess arsenic.

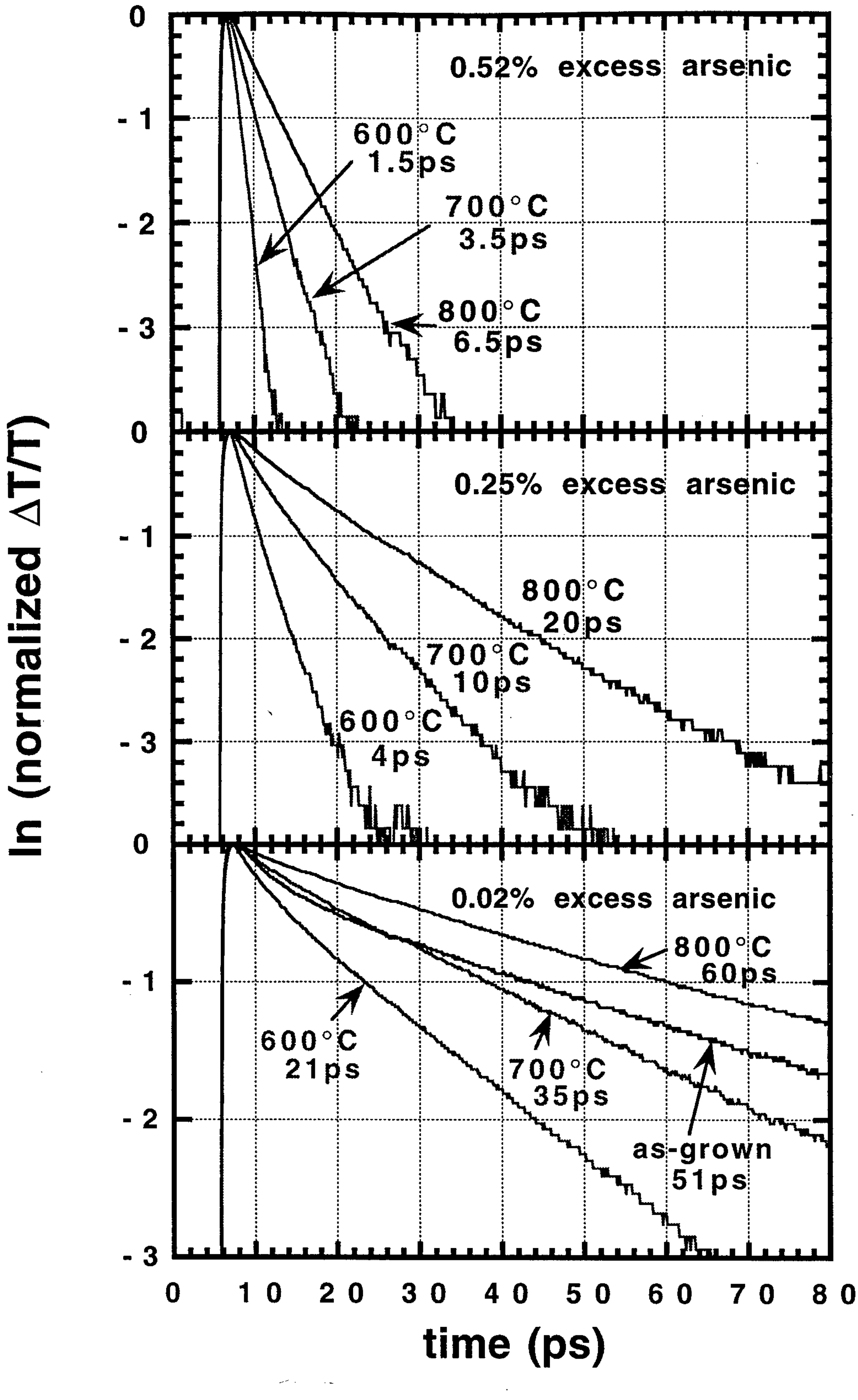


Fig 5. Natural logarithm of normalized differential transmission from a pump/probe measurement of three GaAs epilayers containing 0.52%, 0.25%, and 0.02% excess arsenic. Transients are shown for as-grown material and material that has been annealed for 30 s at 600 °C, 700 °C, and 800 °C.

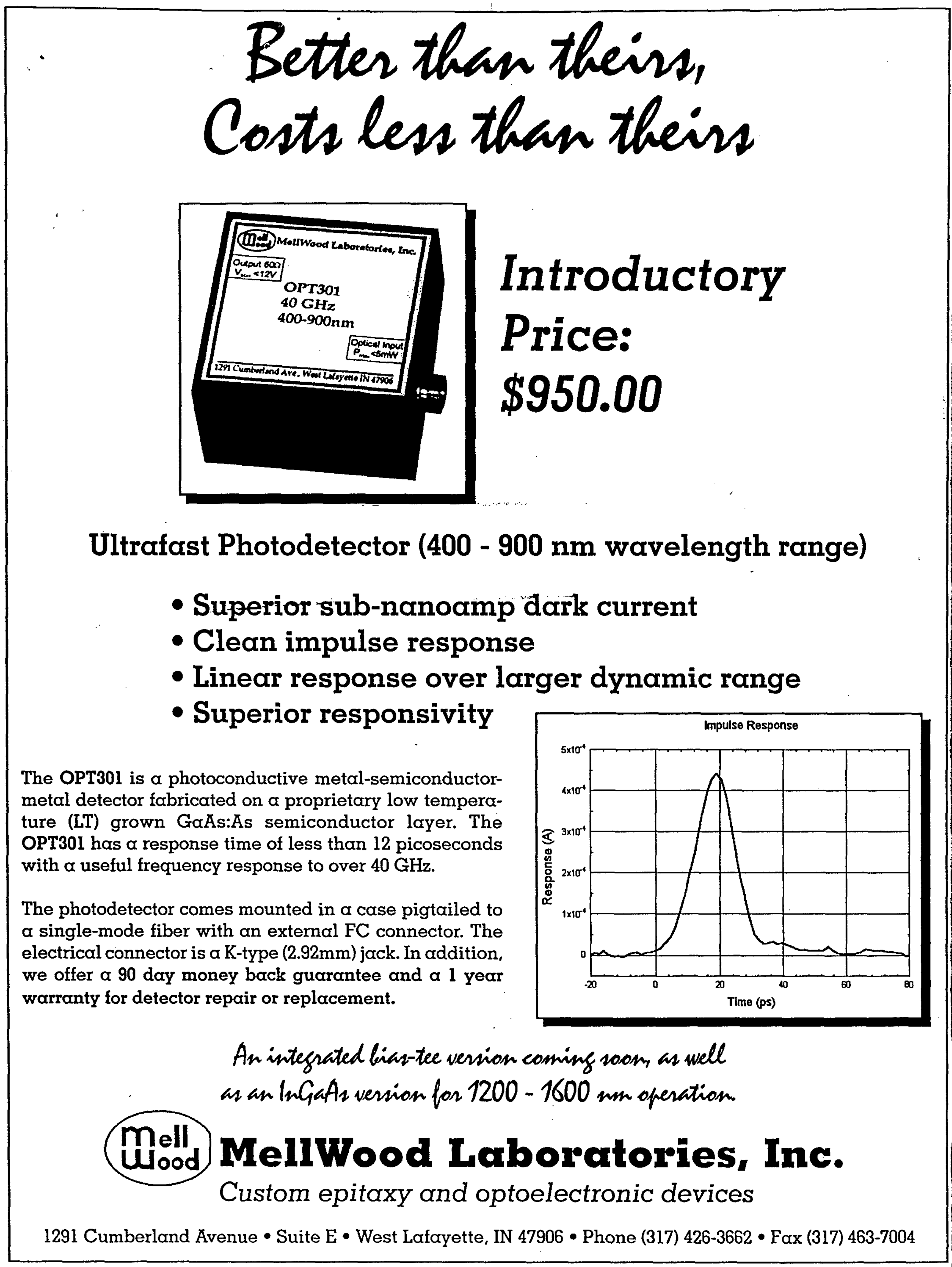


Fig. 6 Advertisement for LTG-GaAs photodetector on the back cover of the January 20, 1997 issue of Applied Physics Letters.